III.B.3 An Innovative Injection and Mixing System for Diesel Fuel Reforming

Objectives

- Develop reliable, cost-effective diesel fuel injection and mixing concepts for use with auto-thermal reformer (ATR) and catalytic partial oxidation reformer (CPOX) in SOFC auxiliary power generation units (APUs).
- Determine operation and performance limitations of four different injection and mixing concepts for diesel fuel reforming applications.
- Optimize the most promising injector/mixer for diesel fuel reformers to operate with minimal steam/water usage and air supply pressure.

Accomplishments

- Completed the design and fabrication of four different fuel injection concepts for a comparative study, including a multipoint impingement injector, a gas-assisted simplex injector, a piezoelectric injector and a preheating simplex injector.
- Conducted detailed computer analysis and characterization of fuel mixture for all four injector concepts using phase Doppler interferometry, Raman spectroscopy, laser extinction tomography and thermocouple measurements.
- Down-selected the most promising injector/mixer and established operation/performance correlation using the statistical design of experiments technique.
- Submitted two patent applications entitled "Fuel Injection and Mixing Systems and Methods of Using the Same" and "Fuel Injection and Mixing Systems Having Piezoelectric Elements and Methods of Using the Same."

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Introduction

Fuel reformers are a very important component of SOFC systems, enabling them to compete with conventional auxiliary power units in remote stationary and mobile power generation markets. Current state-of-the-art fuel reformers are limited to using gaseous fuels, such as natural gas, hydrogen and liquefied petroleum gas (LPG). In the near term, however, liquid hydrocarbon fuels and renewable fuels are the preferred choice for SOFC power systems because of their availability and existing distribution networks.

Currently, liquid fuel processing technology is not yet viable for commercial applications in SOFC systems. One of the major technical barriers for liquid fuel processing is reactor durability. The performance of the reforming catalysts in the reactor quickly deteriorates as a result of carbon deposition, sulfur poisoning and loss of precious metals due to sintering or evaporation at high temperatures. To mitigate these problems, research efforts are being conducted to optimize catalyst materials and to improve fuel reactor design/operation.

Approach

One engineering approach that could alleviate problems associated with liquid fuel reactors is improvement of feed stream preparation. Proper feed stream preparation can significantly improve reactor durability and minimize problems of inadequate fuel atomization, wall impingement, mixture recirculation and non-uniform mixing. These problems can easily lead to local conditions that favor carbon deposition, auto-ignition and formation of hot spots in the reactor. Because liquid fuels are extremely difficult to reform, a proper understanding and selection of injection and mixing systems for feed stream preparation plays an essential role in the development of reliable and durable liquid fuel reformers.

Several promising fuel injection and mixing chamber concepts were proposed for a thorough evaluation using both computational and laser diagnostic techniques. The key performance parameters included in the evaluation were fuel atomization, droplet evaporation and mixing, uniformity of mixture temperature, velocity and concentration, wall impingement, flow recirculation, carbon deposits, feed stream supply pressure, power consumption, complexity and reliability of injector design/operation.

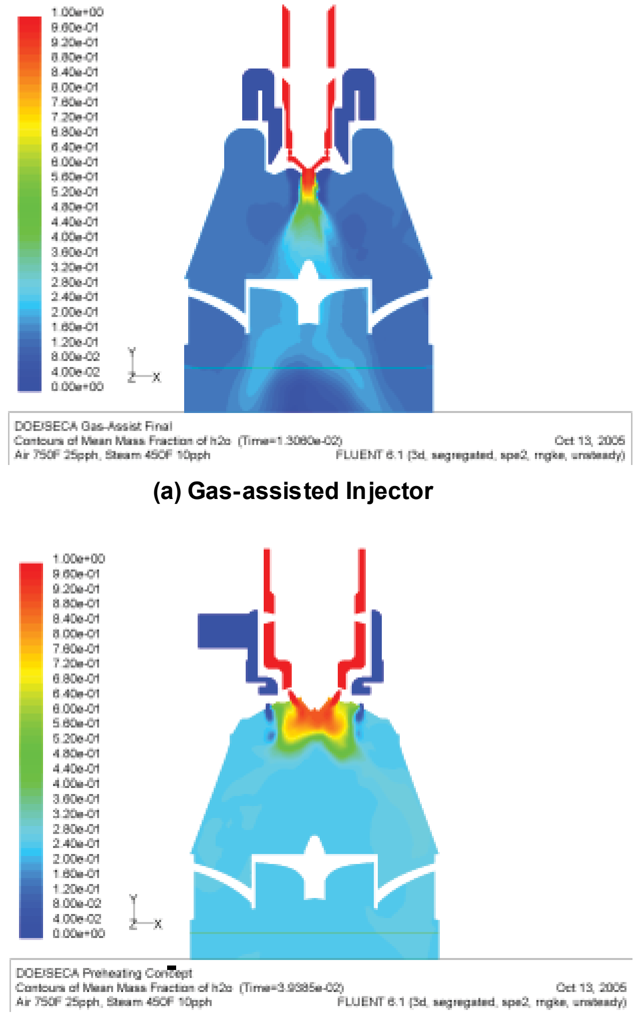
Results

Four injector/mixing chamber concepts have been designed and fabricated for a comparative study, including a multipoint impingement injector, a gas-assisted simplex injector, a high-energy piezoelectric injector and a preheating simplex injector. Based on the experimental and analytical results, relative merits were identified for all injector concepts relating to diesel fuel reforming applications.

Computational fluid dynamics (CFD) was utilized to help predict flow rates, pressure drops and flow non-uniformities associated with design modifications in order to reduce development iterations and cost. CFD was also utilized to simulate the overall flow-field structure and potential mixing capabilities, helping to provide a qualitative assessment of the injector/mixer performance under the actual reformer operating conditions. The computation domain contains a flow path from the feed stream inlets through the injector circuits and the mixing chamber, terminating at the 76.2 mm diameter at the entrance of the catalytic reactor. The grid system for the flow path consists of over 1.8 million tetrahedral and prismatic cells, with clustering tailored to regions of expected high gradients. The solutions were obtained using FLUENT 6.1 software to solve the unsteady, Reynolds-averaged Navier-Stokes equations, with the RNG k-ε turbulence model, wall-functions and differential viscosity models. Figure 1 shows a comparison of time-averaged steam mass fraction in a vertical plane between a gas-assisted injector and a preheating injector. CFD predictions indicated that the preheating injector design produces more uniform temperature and species distributions than the other injector concepts.

For fuel atomization evaluation, detailed measurements were made for all four injector sprays at various operating conditions using phase/Doppler interferometry. Two different measurement methods were utilized to obtain droplet size information: a continuous traverse method and a point-to-point method. The continuous traverse method provides mean droplet diameters that represent the entire spray, and the point-to-point method offers detailed local distributions of droplet size, velocity and fuel volume flux. This information is extremely important to help determine the spray dynamic structure and identify differences between injector concepts. Figure 2 presents a comparison of the radial distribution of Sauter mean diameter (SMD) for the impingement injector, gas-assisted injector and piezoelectric injector at a simulated maximum load condition. The SMD values for the preheating injector are very small, in the sub-micron range, and are not included in Figure 2 for a comparison.

For high-temperature evaluation, the injector/mixer systems were delivered to NASA Glenn Research Center for detailed species measurements using the



(a) Gas-assisted Injector

(b) Preheating Injector

FIGURE 1. A Comparison of Time-Averaged Steam Mass Fraction in a Vertical Plane between a Gas-Assisted Injector and a Preheating Injector

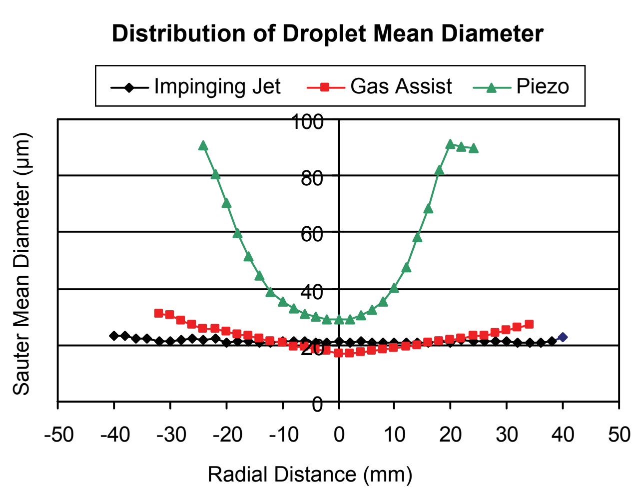


FIGURE 2. A Comparison of the Radial Distribution of SMD for the Impingement Injector, Gas-Assisted Injector and Piezoelectric Injector at a Simulated Maximum Load Condition

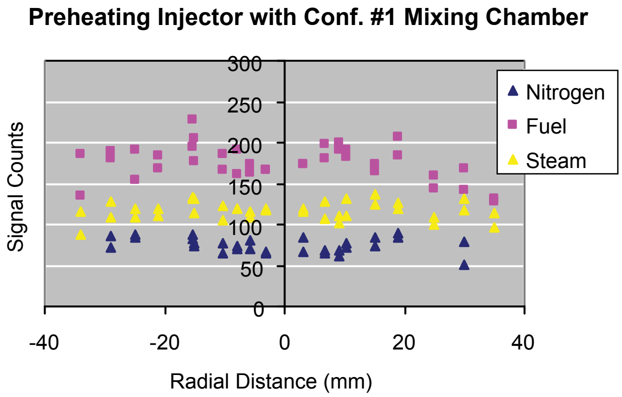


FIGURE 3. Measured Radial Distribution of Species Concentration for a Preheating Simplex Injector Operated with 0.63 g/s Commercial Diesel Fuel, 1.26 g/s Steam at 230°C and 3.15 g/s Airflow at 400°C

Raman spectroscopy instrument. Distributions of fuel, steam and nitrogen were plotted against the radial distances across the flow field to reveal the influence of fuel properties, operating conditions and mixing chamber configurations on feed stream preparation and mixture uniformity. Species measurements were made at an axial distance 65 mm below the mixing chamber exit. The radial distributions of various species were established by making point measurements in 5-mm increments to cover 70 mm of the 75 mm diameter across the flow field. The Raman spectra acquired at various radial locations were processed to determine the area under the Raman peak of each species for signal counts. These signal counts are linearly proportional to the mole fraction of the species detected at the laser probe volume. The higher the signal counts, the higher the species' relative molar fraction is in the flow field. Figure 3 shows the measured species concentration for a preheating simplex injector operating with 0.63 g/s commercial diesel fuel, 1.26 g/s steam at 230°C and 3.15 g/s airflow at 400°C. Compared with the other injector designs, the preheating injector showed the most uniform distribution of species and excellent signal repeatability. During tests, it was observed that the quartz window remained very clean and free of carbon deposits.

Conclusions and Future Directions

- Feed stream preparation and injector selection are extremely important in improving the performance and durability of liquid fuel reformers.
- Extremely fine droplets are required for successful liquid fuel reforming. A SMD value of 15 µm or less may be needed for injector sprays to achieve complete evaporation inside the mixing chamber, in order to mitigate downstream carbon and soot formation.
- The preheating simplex injector appears to be the most promising concept for diesel fuel processing to further the development of SOFC auxiliary power units in commercial diesel truck applications.
- Several operational and technical issues still need to be resolved before incorporating the preheating simplex injector into a practical fuel processing system. These issues include the improvement of injector coking, startup response, fuel fluctuation during load transition and minimizing power consumption.

Special Recognitions & Awards/Patents Issued

1. "Fuel Injection and Mixing Systems and Methods of Using the Same," Patent Pending, April 12, 2006.

2. "Fuel Injection and Mixing Systems Having Piezoelectric Elements and Methods of Using the Same," Patent Pending, December 22, 2005.

FY 2006 Publications/Presentations

1. "Innovative Fuel Injection and Mixing Systems for Diesel Fuel Reforming," SECA 6th Annual Workshop, April 20, 2005, Pacific Grove, CA.

2. "Development of Fuel Injection and Mixing Systems for Diesel Fuel Processing," NETL SECA Fuel Processing Workshop, December 6, 2005, Pittsburgh, PA.

3. "Integrated Injection and Mixing Systems for Diesel Fuel Reforming," U.S. Department of Energy, Office of Fossil Energy Fuel Cell Program, FY 2005 Annual Report.